

## EDGE ARTICLE

View Article Online  
View Journal | View IssueCite this: *Chem. Sci.*, 2020, **11**, 5766

All publication charges for this article have been paid for by the Royal Society of Chemistry

## Facile benzene reduction promoted by a synergistically coupled Cu–Co–Ce ternary mixed oxide†

Hao Chen,<sup>‡ab</sup> Wenwen Lin,<sup>‡a</sup> Zihao Zhang,<sup>‡a</sup> Zhenzhen Yang,<sup>‡b</sup> Kecheng Jie,<sup>‡b</sup> Jie Fu,<sup>‡\*a</sup> Shi-ze Yang,<sup>‡\*d</sup> and Sheng Dai<sup>‡\*bc</sup>

Hydrogenation of aromatic rings promoted by earth-abundant metal composites under mild conditions is an attractive and challenging subject in the long term. In this work, a simple active site creation and stabilization strategy was employed to obtain a Cu<sup>+</sup>-containing ternary mixed oxide catalyst. Simply by pre-treatment of the ternary metal oxide precursor under a H<sub>2</sub> atmosphere, a Cu<sup>+</sup>-derived heterogeneous catalyst was obtained and denoted as Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub>. The catalyst showed (1) high Cu<sup>+</sup> species content, (2) a uniform distribution of Cu<sup>+</sup> doped into the lattices of CoO<sub>x</sub> and CeO<sub>2</sub>, (3) formation of CoO<sub>x</sub>/CuO<sub>x</sub> and CeO<sub>2</sub>/CuO<sub>x</sub> interfaces, and (4) a mesoporous structure. These unique properties of Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub> endow it with pretty high hydrogenation activity for aromatic rings under mild conditions (100 °C with 5 bar H<sub>2</sub>), which is much higher than that of the corresponding binary counterparts and even exceeds the performance of commercial noble metal catalysts (e.g. Pd/C). The synergetic effect plays a crucial role in the catalytic procedure with CeO<sub>2</sub> functioning as a hydrogen dissociation and transfer medium, Cu<sup>+</sup> hydrogenating the benzene ring and CoO<sub>x</sub> stabilizing the unstable Cu<sup>+</sup> species. This will unlock a new opportunity to design highly efficient earth-abundant metal-derived heterogeneous catalysts *via* interface interactions.

Received 20th April 2020

Accepted 14th May 2020

DOI: 10.1039/d0sc02238a

rsc.li/chemical-science

Hydrogenation is one of the central themes of petrochemical, coal chemical, fine chemical and environmental industries and is one of the most intensively investigated topics in catalysis.<sup>1–4</sup> In addition, in the synthesis of fine chemicals, reduction of various functional groups, such as –C=C, –C≡C, –C=O, –NO<sub>2</sub>, –C≡N, –COOH, and –CONH<sub>2</sub>, is required to afford the corresponding alkanes, alkenes, alcohols, and amine products that are key intermediates for the fine chemical, polymer, agrochemical, and pharmaceutical industries, especially using H<sub>2</sub> as a clean and cheap hydrogen source.<sup>5,6</sup> Among all these transformations, hydrogenation of benzene is a direct and important approach to afford cycloalkane intermediates for petrochemical and agrochemical production, and has received enormous attention over the past few decades.<sup>7–9</sup> However, the  $\pi$ -conjugation in aromatic rings makes it one of the most robust

chemical bonds due to high aromaticity and non-polarity.<sup>10–12</sup> Over the past few decades, technologies mainly depending on expensive and precious metal-based catalysts, such as Pd, Ru, Pt, and Ir, have been extensively investigated to facilitate this transformation. Concerns over the scarcity and high cost of noble metals have driven the search for nonprecious earth-abundant alternatives with comparable activity, selectivity and stability, which are greatly desired for scalable and cost-effective chemical transformations.<sup>11–18</sup> To date, there have been a few reports on Ni/Al<sub>2</sub>O<sub>3</sub>, Ni/SiO<sub>2</sub>, Co/SiO<sub>2</sub> and Ni–Al alloys that can partially or fully hydrogenate benzene with transition metal-based catalysts, but harsh reaction conditions (e.g. high reaction temperature up to 200 °C and high H<sub>2</sub> pressure up to 8 MPa) and low weight hourly space velocity (WHSV) limit their further application.<sup>19–21</sup> Therefore, despite intensive studies on the subject of benzene hydrogenation, catalytic systems based on nonprecious metals capable of promoting the reaction under mild conditions are still rarely reported. There are still significant challenges in developing cheap, easily synthesized and highly efficient heterogeneous catalysts derived from earth-abundant alternatives by rational design.

From this aspect, we focus our attention on one of the most challenging kinds of metal species based on copper, which is pretty cheap and abundant. On the other hand, copper-based catalysts have been widely investigated for the hydrogenation

<sup>a</sup>Key Laboratory of Biomass Chemical Engineering of Ministry of Education, College of Chemical and Biological Engineering, Zhejiang University, Hangzhou 310027, China. E-mail: jiefu@zju.edu.cn

<sup>b</sup>Department of Chemistry, University of Tennessee, Knoxville, TN 37996, USA

<sup>c</sup>Chemical Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA. E-mail: dais@ornl.gov

<sup>d</sup>Eyring Materials Center, Arizona State University, Tempe, 85287, USA. E-mail: shize.yang@asu.edu

† Electronic supplementary information (ESI) available. See DOI: 10.1039/d0sc02238a

‡ These authors contributed equally.

of biomass<sup>22,23</sup> and CO<sub>2</sub>,<sup>24–27</sup> with the activity being mainly attributed to the Cu<sup>0</sup> species in vapor-phase reactions.<sup>23,28</sup> For instance, Ma *et al.* revealed that the formation rate of alcohol is strongly correlated with the density of surface Cu<sup>0</sup> sites.<sup>25,29</sup> Notably, compared with Cu<sup>0</sup> and Cu<sup>2+</sup>, Cu<sup>+</sup> has a higher hydrogenation activity considering its intrinsic ability to facilitate electron transfer through gaining or losing an electron.<sup>25,30,31</sup> Many studies have reported that Cu<sup>0</sup>/Cu<sup>+</sup> leads to an enhanced catalytic activity for hydrogenation, which is attributed to the activation of the ester groups by Cu<sup>+</sup> species in the production of alcohols.<sup>30,32–34</sup> However, these conjectures are inconclusive as obtaining Cu<sup>+</sup> is synthetically challenging due to its tendency to easily oxidize to Cu<sup>2+</sup> or reduce to Cu<sup>0</sup> during catalyst preparation and processing. The key to success lies in the design and fabrication of copper-containing composites capable of stabilizing the highly active Cu<sup>+</sup> species through interface interactions. This will also enable a deeper understanding of the catalytic contributions from the Cu<sup>+</sup> species, which is significant for the rational design of active hydrogenation catalysts.

As previously reported, the CoO<sub>y</sub> in Cu catalyst not only enhances the metallic Cu dispersion and H<sub>2</sub> activation ability, but also modifies the chemical states of Cu to create suitable surface Cu<sup>0</sup>/Cu<sup>+</sup> distributions due to strong electronic interactions at the Cu/CoO<sub>x</sub> interface.<sup>35</sup> This inspires us to fabricate multi-component heterogeneous catalysts containing Cu<sup>+</sup> species. It is known that the adsorption and activation of H<sub>2</sub> constitutes another critical step in the hydrogenation reactions. Various kinds of materials have been reported to activate H<sub>2</sub> by homolytic or heterolytic dissociation.<sup>36,37</sup> Recently, Sai *et al.* created solid frustrated Lewis pairs (FLPs) on the surface of CeO<sub>2</sub> by regulating their surface defects. The resultant catalysts exhibited H<sub>2</sub> dissociation ability with a low activation barrier and delivered a high catalytic activity for hydrogenation of alkenes and alkynes, as well as transformation of CO<sub>2</sub>.<sup>38,39</sup> However, the catalytic activity of these CeO<sub>2</sub>-based materials is still insufficient to achieve hydrogenation of aromatic rings. Therefore, we expect that the combination of Cu, Co and Ce species will create enhanced H<sub>2</sub> activation capability, realize the hydrogenation of aromatic rings under mild conditions through a synergistic effect, and lead to further understanding of the interface interaction during the catalytic procedure.

In previous studies, our group developed a simple fabrication procedure to obtain a ternary CuO–Co<sub>3</sub>O<sub>4</sub>–CeO<sub>2</sub> catalyst, which showed excellent catalytic activity for CO oxidation.<sup>40</sup> Herein, a simple active site creation and stabilization strategy was employed to obtain a Cu<sup>+</sup>-containing ternary mixed oxide catalyst. Simply by pre-treatment of the ternary metal oxide precursor under a H<sub>2</sub> atmosphere, a Cu<sup>+</sup>-derived heterogeneous catalyst was obtained and denoted as Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub>. The catalyst showed (1) high Cu<sup>+</sup> species content, (2) a uniform distribution of Cu<sup>+</sup> doped into the lattices of CoO<sub>x</sub> and CeO<sub>2</sub>, (3) formation of CoO<sub>y</sub>/CuO<sub>x</sub> and CeO<sub>2</sub>/CuO<sub>x</sub> interfaces, and (4) a mesoporous structure. These unique properties of Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub> endow it with pretty high hydrogenation activity for aromatic rings under mild conditions (100 °C with 5 bar H<sub>2</sub>), which is much higher than that of the corresponding binary counterparts and even

exceeds the performance of commercial noble metal catalysts (*e.g.* Pd/C). The synergistic effect plays a crucial role in the catalytic procedure with CeO<sub>2</sub> functioning as a hydrogen dissociation and transfer medium, Cu<sup>+</sup> hydrogenating the benzene ring and CoO<sub>x</sub> stabilizing the unstable Cu<sup>+</sup> species. This will unlock a new opportunity to design highly efficient earth-abundant metal-derived heterogeneous catalysts *via* interface interactions.

The ternary Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub> catalyst was prepared *via* a two-step approach involving co-precipitation and heat-treatment. Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>y</sub> with a Cu : Co : Ce atomic ratio of 1 : 5 : 5 was first synthesized using a co-precipitation method,<sup>40,41</sup> and further pre-treatment at 100 °C with 5 bar H<sub>2</sub> for 24 h leads to the formation of Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub>. The ICP result shown in Table S1† confirmed that the Cu : Co : Ce atomic ratio was almost the same as that calculated from the raw ratio. The XRD pattern of Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>y</sub> in Fig. 1a suggests that the as-synthesized ternary oxides are composed of crystalline CeO<sub>2</sub> and Co<sub>3</sub>O<sub>4</sub>. After H<sub>2</sub> heat-treatment, no change in the diffraction peaks of CeO<sub>2</sub> and Co<sub>3</sub>O<sub>4</sub> was found in Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub>. Then, we compared the XRD pattern of CeO<sub>2</sub> (PDF#81-0792),<sup>42</sup> Co<sub>3</sub>O<sub>4</sub> (PDF-74-1657)<sup>43</sup> and Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub> as shown in Fig. 1(a) to further prove that Cu is doped into the lattices of CoO<sub>y</sub> and CeO<sub>2</sub> in Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub>. It was found that the XRD peaks for Ce and Co in Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub> shifted to lower 2 theta angle, which means a larger lattice parameter of the CeO<sub>2</sub> and Co<sub>3</sub>O<sub>4</sub> in Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub> than the pure CeO<sub>2</sub> and Co<sub>3</sub>O<sub>4</sub> after the introduction of copper species, as well as providing evidence to show that the Cu ions are incorporated into the CeO<sub>2</sub> and Co<sub>3</sub>O<sub>4</sub> crystallites in Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub>.<sup>42,44</sup> Then we investigated the structure of CuCoO<sub>x</sub> (Cu : Co = 1 : 10 mole ratio), CuCeO<sub>x</sub> (Cu : Ce = 1 : 10 mole ratio) and CoCeO<sub>x</sub> (Ce : Co = 1 : 1 mole ratio) by XRD and the results are shown in Fig. S1.† The results showed that the 10 mol% Cu dispersed well in the CoO<sub>x</sub> and CeO<sub>x</sub> with almost no Cu XRD peak observed. Thus, in this work, the Cu uniformly distributed among CoO<sub>y</sub> and CeO<sub>2</sub>, respectively. XPS was performed to probe the oxidation states of Co and Cu on the surface of the ternary oxides. As shown in Fig. 1b–d, both Cu 2p and Co 2p peaks exhibit peak shifts towards lower energies, indicating that the H<sub>2</sub> pre-treatment significantly reduces the surface of Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>y</sub> and partially lowers the oxidation states of the metal species (Cu<sup>2+</sup> 934.1 eV, Co<sup>3+</sup> 781.2 eV, Cu<sup>+</sup>/Cu<sup>0</sup> 932.0 eV and Co<sup>2+</sup> 779.2 eV, Table S2†).<sup>45</sup> Considering the overlap of the XPS peaks corresponding to Cu<sup>+</sup> and Cu<sup>0</sup>, we turned to Cu LMM to determine the Cu oxidation states in the ternary oxide catalysts (Fig. 1d and S2†), where only Cu<sup>2+</sup> (569.3 eV) was observed in the Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>y</sub> catalyst while only Cu<sup>+</sup> (573.2 eV) was observed in the Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub> catalyst.<sup>46–48</sup> Therefore, the spectroscopic results indicate that Cu<sup>+</sup> and Co<sup>2+</sup> are formed on the surface of Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub> after the H<sub>2</sub> pre-treatment. CeO<sub>2</sub> exhibits hydrogenation activity for unsaturated compounds as the oxidation states of Ce can change reversibly between Ce<sup>4+</sup> under oxidizing conditions and Ce<sup>3+</sup> under reducing conditions.<sup>49,50</sup> As shown in Fig. 1e, XPS has been performed for Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>y</sub> and Cu<sub>1</sub>Co<sub>5</sub>Ce<sub>5</sub>O<sub>x</sub> to distinguish between the Ce<sup>4+</sup> and Ce<sup>3+</sup> species, where the shifting of peaks to lower



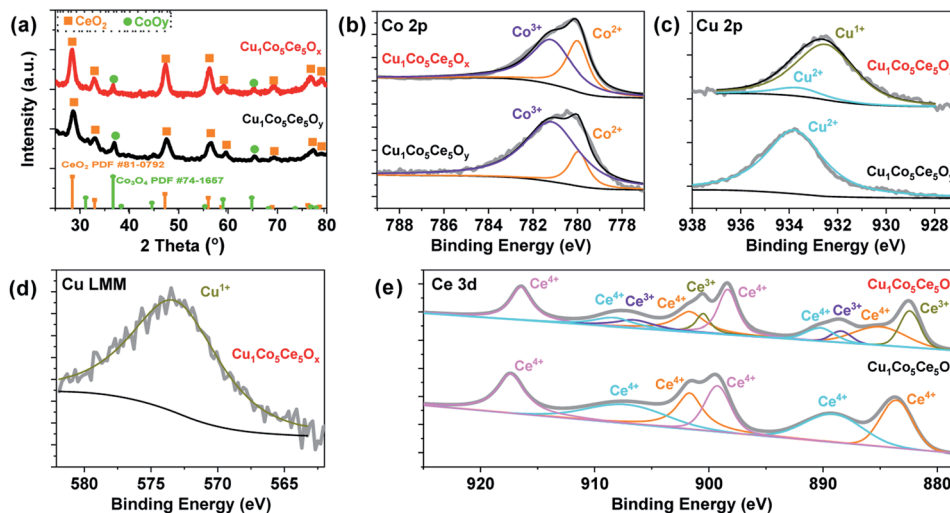


Fig. 1 (a) XRD patterns, and (b) XPS results of Co 2p, (c) Cu 2p, (d) Cu-LMM, and (e) Ce 3d in  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_y$  and  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  obtained before and after pre-treatment under 5 bar  $\text{H}_2$  and 100 °C temperature for 24 h.

binding energy may be due to a higher proportion of  $\text{Ce}^{3+}$ .<sup>50</sup> Chen *et al.*<sup>51</sup> reported that active Cu clusters consist of  $\text{Cu}^0$  at the top layer and  $\text{Cu}^+$  species at the Cu/ $\text{CeO}_2$  interface due to electron depletion caused by the oxygen vacancies ( $\text{O}_v$ ) in  $\text{CeO}_2$ . In our case, the  $\text{H}_2$  pre-treatment may create more oxygen vacancies which stabilize  $\text{Cu}^+$  through forming  $\text{Cu}^+-\text{O}_v-\text{Ce}^{3+}$  interfacial bonds. It was found that the Cu species in  $\text{CuCoCeO}_y$  after pre-treatment for 6 h and 18 h were almost maintained at the  $\text{Cu}^{2+}$  state (Fig. S3†). However, it seemed that the Co was easily reduced and more  $\text{Co}^{2+}$  was formed compared with the  $\text{CuCoCeO}_y$  after pre-treatment for 6 h and 18 h. And for Ce, the Ce in  $\text{CuCoCeO}_y$  after pre-treatment for 6 h have no significant change compared with the starting material, with all the Ce species in the state of  $\text{Ce}^{4+}$ . After pre-treatment for 18 h, a small amount of  $\text{Ce}^{3+}$  formed.

As reported in our previous work,<sup>40,41</sup> the as-synthesized  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_y$  without  $\text{H}_2$  treatment showed a structure with copper-ceria and cobalt-ceria interfaces (Fig. S4†). To further probe the structural details of the ternary  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  as well as the interface of  $\text{CoO}_y(\text{Cu}_2\text{O})-\text{CeO}_2(\text{Cu}_2\text{O})$ , STEM-HAADF with EDS elemental mapping was conducted as shown in Fig. 2. The absence of the diffraction peaks corresponding to Cu,  $\text{Cu}_2\text{O}$ , or  $\text{CuO}$  in the XRD pattern (Fig. 1a), together with a uniform distribution of Cu among  $\text{CoO}_y$  and  $\text{CeO}_2$  in the STEM-EDS elemental maps (Fig. 2), suggests that Cu is doped into the lattices of  $\text{CoO}_y$  and  $\text{CeO}_2$  for  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  and forms  $\text{CoO}_y/\text{CuO}_x$  and  $\text{CeO}_2/\text{CuO}_x$  interfaces.

The  $\text{N}_2$  adsorption-desorption isotherm at 77 K is shown in Fig. 3a and the sample exhibits a typical type IV shape isotherm, suggesting the existence of mesopores with 2–10 nm pore diameters in  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  after  $\text{H}_2$  treatment. The Brunauer-Emmett-Teller (BET) surface area of the  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  is estimated to be  $82 \text{ m}^2 \text{ g}^{-1}$  with a total pore volume of  $0.13 \text{ m}^3 \text{ g}^{-1}$  (Fig. 3), which is a little higher compared with that of the  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_y$  before  $\text{H}_2$  treatment ( $78 \text{ m}^2 \text{ g}^{-1}$ ). Notably, mesopores played a dominant role in the pore structure, contributing ~99% of the total pore volume ( $V_{\text{micro}} = 0 \text{ m}^3 \text{ g}^{-1}$ , calculated using the *t*-plot method). For catalytic or adsorptive materials, a high surface area together with a mesoporous structure can dramatically enhance their reactivity due to an improved mass transfer effect.<sup>52,53</sup>

Acetyl benzene is selected as a model substrate to evaluate the catalytic properties of  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  (Fig. 4a). In a typical catalytic experiment, 100 mg of  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_y$  was pre-treated at 100 °C with 5 bar  $\text{H}_2$  for 24 h. Then 150 mg acetyl benzene (A) and 5 mL hexane were added to the reaction solution for hydrogenation under the same conditions. The  $\text{H}_2$ -pretreated ternary oxide catalyst  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  exhibits excellent activity towards complete hydrogenation of both acetyl and benzene groups, producing ethylcyclohexane (D) with 100% conversion and 97% yield, which even exceeds the performance of

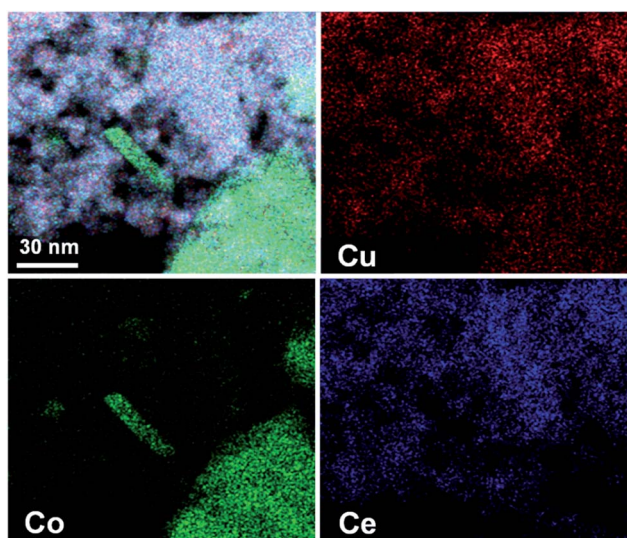


Fig. 2 STEM-HAADF images and EDS elemental mapping images of Cu, Co and Ce in the  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  catalyst.





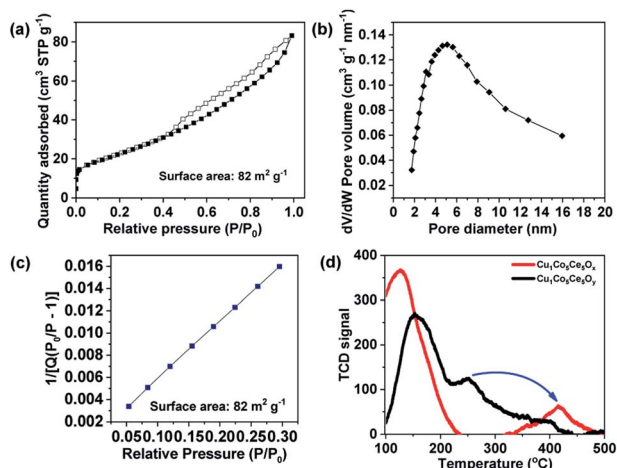


Fig. 3 (a)  $N_2$  adsorption/desorption isotherm at 77 K, (b) pore size distribution curve, (c) BET plot, and (d) benzene temperature programmed desorption of  $Cu_1Co_5Ce_5O_x$  and  $Cu_1Co_5Ce_5O_y$  catalysts.

commercial 5 wt% Pd/C catalysts (74% conversion and 72% yield) under the same reaction conditions (Fig. 4b). Further control experiments show that the untreated ternary oxide catalyst  $Cu_1Co_5Ce_5O_y$  exhibited much inferior hydrogenation capability, with ethylbenzene (C) being obtained as the sole product (Fig. S5†). To further investigate the synergistic effect of the ternary oxides,  $H_2$ -pretreated binary oxide catalysts

including  $CuCeO_x$ ,  $CuCoO_x$ , and  $CoCeO_x$  were prepared and the catalytic results indicated that ethylbenzene (C) was obtained in the presence of  $CuCeO_x$  and  $CuCoO_x$ , and when using  $CoCeO_x$  as the catalyst, only reduction of the carbonyl group can be achieved, affording 1-phenylethanol as the product. That is, none of them showed the ability to hydrogenate the benzene ring. In addition, selective hydrogenation was realized using catalysts obtained by pre-treating  $Cu_1Co_5Ce_5O_y$  under hydrogen with different times. Then, the XPS spectra of the  $CuCoO_x$  and  $CuCeO_x$  were measured (Fig. S6†). It can be found that without the synergistic effect of  $CoO_x$  and  $CeO_x$ , the Cu species in  $CuCoO_x$  and  $CuCeO_x$  after  $H_2$  pre-treatment all existed as  $Cu^{2+}$  and  $Cu^0$ , and controlled reduction to  $Cu^+$  cannot be achieved. This was also proved by CODRIFTS as shown in Fig. S7†. Therefore,  $Cu^+$  was the key factor in this work to achieve successful hydrogenation of the benzene ring. The generated  $Cu_1Co_5Ce_5O_x$  catalysts exhibited distinct hydrogenation capabilities. As summarized in Fig. 4c,  $H_2$ -pretreatments for 6 h, 18 h, and 24 h lead to the formation of 96% ethyl benzene (C), 98% ethyl benzene (C), and 97% ethyl cyclohexane (D), respectively. Therefore, the  $H_2$ -pretreated ternary Cu-Co-Ce oxides show an excellent capability towards the hydrogenation of aromatic rings.

As previously reported, compared with  $Cu^0$  and  $Cu^{2+}$ ,  $Cu^+$  has a higher hydrogenation activity considering its intrinsic ability to facilitate electron transfer through gaining or losing an electron.<sup>25,30,31</sup> Many studies have reported that  $Cu^0/Cu^+$  leads to

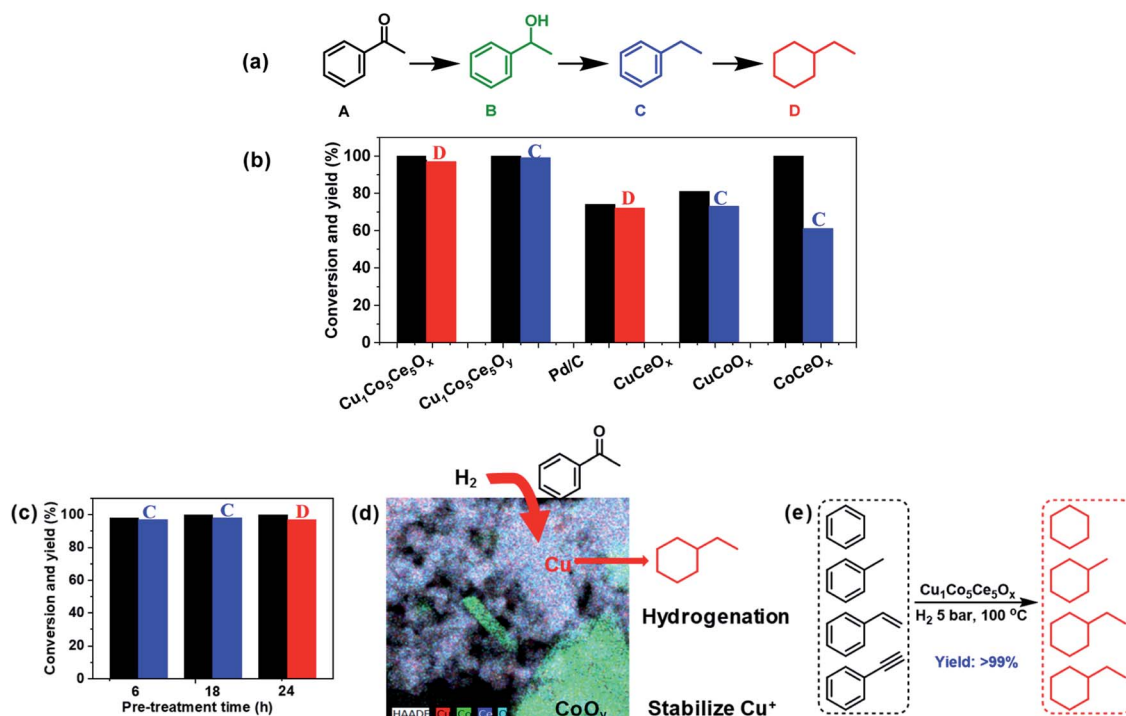


Fig. 4 (a) Catalytic hydrodeoxygenation of acetyl benzene. (b) Comparison of the catalytic activity using  $Cu_1Co_5Ce_5O_x$ ,  $Cu_1Co_5Ce_5O_y$ , Pd/C,  $CuOCoO_2$ ,  $CoO_yCeO_2$ , and  $CuOCoO_y$  after  $H_2$  pretreatment. (c) Catalytic hydrodeoxygenation of acetyl benzene over the  $Cu_1Co_5Ce_5O_y$  catalyst with different pre-treatment times. (d) Synergistic effect of  $Cu_2O$ ,  $CoO_y$  and  $CeO_2$  in the CCC catalyst. (e) Hydrogenation of other aromatic compounds containing the benzene ring. All the reactions were performed under the following conditions: catalyst (100 mg), hexane (5 mL), substrate (1.25 mmol), reaction time (24 h), temperature (100 °C),  $H_2$  (5 bar). Acetyl benzene was used as the substrate for the results in (a) and (b).



an enhanced catalytic activity for hydrogenation, which is attributed to the activation of the ester groups by  $\text{Cu}^+$  species.<sup>30,33,34</sup> However, it is difficult to isolate  $\text{Cu}^+$  species for direct comparison, as it can rapidly convert to  $\text{Cu}^0$  or  $\text{Cu}^{2+}$  during catalyst preparation and processing. Here we report a ternary oxide system  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  where  $\text{Cu}^+$  can be formed and stabilized through a simple pretreatment under  $\text{H}_2$ . As previously reported, the  $\text{CoO}_y$  in Cu catalyst not only enhances the metallic Cu dispersion and  $\text{H}_2$  activation ability, but also modifies the chemical states of Cu to create suitable surface  $\text{Cu}^0/\text{Cu}^+$  distributions due to strong electronic interactions at the Cu/ $\text{CoO}_x$  interface.<sup>35</sup> In our case, Cu is doped into the lattices of  $\text{CoO}_y$  and  $\text{CeO}_2$  for  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  and  $\text{CoO}_y$  exists as a promoter to stabilize  $\text{Cu}^+$  under 5 bar  $\text{H}_2$  and 100 °C through interfacial effects with  $\text{CeO}_2$ . This is further supported by the emergence of  $\text{Cu}^0$  after the pretreatment of  $\text{CuCeO}_x$  (Fig. S6 and S7†), indicating that  $\text{Cu}^{2+}$  will be reduced to  $\text{Cu}^0$  without cobalt. The stabilized  $\text{Cu}^+$  in  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  exhibits an excellent catalytic performance for the hydrogenation of both benzene and  $\text{C}=\text{O}$ , while  $\text{CuCeO}_x$ ,  $\text{CuCoO}_x$ , and  $\text{CoCeO}_x$  exhibit limited conversion and selectivity of converting acetyl benzene to ethylcyclohexane. It was also reported that the defect-enriched  $\text{CeO}_2$  constructed interfacial frustrated Lewis pairs ( $\text{Ce}^{3+}\cdots\text{O}^{2-}$ ) that effectively activate the  $\text{H}_2$  and  $\text{CO}_2$  (ref. 38 and 39) and XPS results show that the  $\text{H}_2$  pretreatment led to the formation of  $\text{Ce}^{3+}$  with oxygen vacancies on the surface. Chen *et al.*<sup>51</sup> also reported that the  $\text{Cu}^+$  species directly bonded to the oxygen vacancy in  $\text{CeO}_2$  exhibits a high activity for the water-gas shift reaction, where the  $\text{Cu}^+$  site chemically adsorbs CO while the neighbouring  $\text{O}_v\text{-Ce}^{3+}$  site activates  $\text{H}_2\text{O}$ . Thus,  $\text{CeO}_2$  functions as a hydrogen dissociation and transfer medium *via* the  $\text{Ce}^{3+}\cdots\text{O}^{2-}$  frustrated Lewis pairs<sup>54</sup> and then the neighbouring  $\text{Cu}^+$  hydrogenates the benzene as shown in Fig. 4d. In addition, benzene temperature programmed desorption (Ben-TPD) was performed to study the adsorption capacity of the benzene ring on  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_y$  and  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  catalysts as shown in Fig. 3d. The two observed peaks at 100–200 and 250–450 °C are attributed to physical and chemical adsorption of benzene on the two oxide catalysts, respectively. Clearly, chemisorption of benzene on  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_y$  is enhanced after  $\text{H}_2$  pretreatment as evidenced by the increase in desorption temperature from 250 °C to 420 °C, probably due to the strong interaction between benzene and a withdrawing  $\text{Cu}^+$  from the oxygen ring.<sup>55</sup> Besides acetyl benzene, a series of benzene and benzene derivatives including benzene, phenylacetylene and methylbenzene are also fully hydrogenated to the corresponding alkanes using the  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  catalyst under mild conditions (Fig. 4e), demonstrating the wide applicability of the ternary oxides for efficient benzene hydrogenation. In summary, a new type of Cu–Co–Ce ternary mixed oxide catalyst with remarkable hydrogenation activity of benzene is reported. Formation of  $\text{Cu}^+$  during a simple pretreatment process is considered to be key to the activity promotion, while  $\text{CoO}_x$  functions as the  $\text{Cu}^+$  stabilizer and  $\text{CeO}_2$  facilitates the dissociation and transfer of hydrogen. Demonstration of  $\text{Cu}^+$  in  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  as the key component leading to extraordinary hydrogenation activity of substituted benzenes provides new insights into the design and

modification of noble-metal-free catalysts for a wide scope of heterogeneous transformations. The resultant turnover number (TON) using  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_y$ ,  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  and commercial 5 wt% Pd/C in this work was compared. The TON obtained in different catalytic systems was estimated based on the following equation:  $\text{TON} = \text{mmol (ethylbenzene)}/\text{mmol (active site)}$ .<sup>56,57</sup> As a result, the TON of the  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_y$ ,  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  and commercial 5 wt% Pd/C was calculated to be 0, 38.8 and 18.6. It was found that the  $\text{Cu}_1\text{Co}_5\text{Ce}_5\text{O}_x$  obtained after  $\text{H}_2$  pretreatment exhibited a TON value double that obtained using a Pd/C catalyst. The results of stability during five cycles of reuse as well as the XPS and XRD measurements are shown in Fig. S8–S10.† It was found that the  $\text{Cu}^+$  remained in the  $1^+$  valence state after the hydrogenation (Fig. S8†). This is because the catalyst was pre-treated under the same conditions as the reaction conditions. Thus, during the reaction process within 24 h, the catalyst was stable and there should be no change of valence state during the catalytic recycling (Fig. S10†). The catalytic results revealed that the catalyst showed very good reusability for at least five cycles without any decrease in the catalytic activity, with >99% conversion of acetyl benzene and >95% yield of ethylcyclohexane being obtained in the fifth run. And the XRD results showed that the structure of the recycled catalyst was maintained well after catalyzing the hydrogenation reaction.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

HC, ZZY, KCJ, and SD were supported by the Division of Chemical Sciences, Geosciences, and Biosciences, Office of Basic Energy Sciences, U.S. Department of Energy. JF was supported by the National Natural Science Foundation of China (No. 21978259 and 21706228), the Zhejiang Provincial Natural Science Foundation of China (No. LR17B060002) and the Fundamental Research Funds for the Central Universities. The STEM characterization used resources of the Center for Functional Nanomaterials, which is a U.S. DOE Office of Science Facility, at Brookhaven National Laboratory under Contract No. DE-SC0012704.

## Notes and references

- 1 R. A. Johnstone, A. H. Wilby and I. D. Entwistle, *Chem. Rev.*, 1985, **85**, 129–170.
- 2 F. Meemken and A. Baiker, *Chem. Rev.*, 2017, **117**, 11522–11569.
- 3 D. Wang and D. Astruc, *Chem. Rev.*, 2015, **115**, 6621–6686.
- 4 L. Zhang, M. Zhou, A. Wang and T. Zhang, *Chem. Rev.*, 2020, **120**, 683–733.
- 5 L. Alig, M. Fritz and S. Schneider, *Chem. Rev.*, 2018, **119**, 2681–2751.
- 6 W. Wang, S. Wang, X. Ma and J. Gong, *Chem. Soc. Rev.*, 2011, **40**, 3703–3727.



- 7 S. Miao, Z. Liu, B. Han, J. Huang, Z. Sun, J. Zhang and T. Jiang, *Angew. Chem. Int. Ed.*, 2006, **45**, 266–269.
- 8 C. P. Rader and H. A. Smith, *J. Am. Chem. Soc.*, 1962, **84**, 1443–1449.
- 9 L. Foppa and J. Dupont, *Chem. Soc. Rev.*, 2015, **44**, 1886–1897.
- 10 X. Kang, G. Luo, L. Luo, S. Hu, Y. Luo and Z. Hou, *J. Am. Chem. Soc.*, 2016, **138**, 11550–11559.
- 11 H. Liu, R. Fang, Z. Li and Y. Li, *Chem. Eng. Sci.*, 2015, **122**, 350–359.
- 12 C. Hubert, E. G. Bilé, A. Denicourt-Nowicki and A. Roucoux, *Green Chem.*, 2011, **13**, 1766–1771.
- 13 H. Liu, T. Jiang, B. Han, S. Liang and Y. Zhou, *Science*, 2009, **326**, 1250–1252.
- 14 P. Zhang, T. Wu, T. Jiang, W. Wang, H. Liu, H. Fan, Z. Zhang and B. Han, *Green Chem.*, 2013, **15**, 152–159.
- 15 K. M. Bratlie, H. Lee, K. Komvopoulos, P. Yang and G. A. Somorjai, *Nano Lett.*, 2007, **7**, 3097–3101.
- 16 C. Vangelis, A. Bouriazos, S. Sotiriou, M. Samorski, B. Gutsche and G. Papadogianakis, *J. Catal.*, 2010, **274**, 21–28.
- 17 P. Tomkins, E. Gebauer-Henke, W. Leitner and T. E. Müller, *ACS Catal.*, 2014, **5**, 203–209.
- 18 J.-F. Yuan, C.-Q. Luo, Q. Yu, A.-P. Jia, G.-S. Hu, J.-Q. Lu and M.-F. Luo, *Catal. Sci. Technol.*, 2016, **6**, 4294–4305.
- 19 X. Kang, H. Liu, M. Hou, X. Sun, H. Han, T. Jiang, Z. Zhang and B. Han, *Angew. Chem., Int. Ed.*, 2016, **55**, 1080–1084.
- 20 R. Molina and G. Poncelet, *J. Catal.*, 2001, **199**, 162–170.
- 21 L. Lu, Z. Rong, W. Du, S. Ma and S. Hu, *ChemCatChem*, 2009, **1**, 369–371.
- 22 Z. Zhang, Q. Yang, H. Chen, K. Chen, X. Lu, O. Pingkai, J. Fu and J. G. Chen, *Green Chem.*, 2017, **20**, 197–205.
- 23 Z. Zhang, S. Yao, C. Wang, M. Liu, F. Zhang, X. Hu, H. Chen, X. Gou, K. Chen, Y. Zhu, X. Lu, P. Ouyang and J. Fu, *J. Catal.*, 2019, **373**, 314–321.
- 24 B. An, J. Zhang, K. Cheng, P. Ji, C. Wang and W. Lin, *J. Am. Chem. Soc.*, 2017, **139**, 3834–3840.
- 25 J. Gong, H. Yue, Y. Zhao, S. Zhao, L. Zhao, J. Lv, S. Wang and X. Ma, *J. Am. Chem. Soc.*, 2012, **134**, 13922–13925.
- 26 Z.-Q. Wang, Z.-N. Xu, S.-Y. Peng, M.-J. Zhang, G. Lu, Q.-S. Chen, Y. Chen and G.-C. Guo, *ACS Catal.*, 2015, **5**, 4255–4259.
- 27 S. Kattel, P. J. Ramírez, J. G. Chen, J. A. Rodriguez and P. Liu, *Science*, 2017, **355**, 1296–1299.
- 28 R. Reske, H. Mistry, F. Beharfarid, B. R. Cuenya and P. Strasser, *J. Am. Chem. Soc.*, 2014, **136**, 6978–6986.
- 29 S. Zhao, H. Yue, Y. Zhao, B. Wang, Y. Geng, J. Lv, S. Wang, J. Gong and X. Ma, *J. Catal.*, 2013, **297**, 142–150.
- 30 X. Chang, T. Wang, Z. J. Zhao, P. Yang, J. Greeley, R. Mu, G. Zhang, Z. Gong, Z. Luo, J. Chen, Y. Cui, G. A. Ozin and J. Gong, *Angew. Chem. Int. Ed.*, 2018, **57**, 15415–15419.
- 31 W. Chen, T. Song, J. Tian, P. Wu and X. Li, *Catal. Sci. Technol.*, 2019, **9**, 6749–6759.
- 32 C. Wen, A. Yin, Y. Cui, X. Yang, W.-L. Dai and K. Fan, *Appl. Catal., A*, 2013, **458**, 82–89.
- 33 Y. Wang, Y. Shen, Y. Zhao, J. Lv, S. Wang and X. Ma, *ACS Catal.*, 2015, **5**, 6200–6208.
- 34 S. Zhang, Y. Ma, H. Zhang, X. Zhou, X. Chen and Y. Qu, *Angew. Chem. Int. Ed.*, 2017, **56**, 8245–8249.
- 35 J. Wu, G. Gao, P. Sun, X. Long and F. Li, *ACS Catal.*, 2017, **7**, 7890–7901.
- 36 D. Teschner, J. Borsodi, A. Wootsch, Z. Révay, M. Hävecker, A. Knop-Gericke, S. D. Jackson and R. Schlögl, *Science*, 2008, **320**, 86–89.
- 37 T. Mitsudome, Y. Mikami, M. Matoba, T. Mizugaki, K. Jitsukawa and K. Kaneda, *Angew. Chem. Int. Ed.*, 2012, **51**, 136–139.
- 38 S. Zhang, Z. Xia, Y. Zou, F. Cao, Y. Liu, Y. Ma and Y. Qu, *J. Am. Chem. Soc.*, 2019, **141**, 11353–11357.
- 39 S. Zhang, Z. Q. Huang, Y. Ma, W. Gao, J. Li, F. Cao, L. Li, C. R. Chang and Y. Qu, *Nat. Commun.*, 2017, **8**, 15266.
- 40 A. J. Binder, T. J. Toops, R. R. Unocic, J. E. Parks and S. Dai, *Angew. Chem. Int. Ed.*, 2015, **54**, 13263–13267.
- 41 W. Xiao, S. Yang, P. Zhang, P. Li, P. Wu, M. Li, N. Chen, K. Jie, C. Huang, N. Zhang and S. Dai, *Chem. Mater.*, 2018, **30**, 2924–2929.
- 42 C. He, Y. Yu, L. Yue, N. Qiao, J. Li, Q. Shen, W. Yu, J. Chen and Z. Hao, *Appl. Catal., B*, 2014, **147**, 156–166.
- 43 Y. Tak and K. Yong, *J. Phys. Chem. C*, 2008, **112**, 74–79.
- 44 N. R. Radwan, M. Mokhtar and G. A. El-Shobaky, *Appl. Catal., A*, 2003, **241**, 77–90.
- 45 H. Yan, H. Qin, W. Liang, X. Jin, Y. Zhang, X. Feng, Y. Liu, X. Chen and C. Yang, *Catal. Sci. Technol.*, 2019, **9**, 4909–4919.
- 46 Y. Tanaka, R. Kikuchi, T. Takeguchi and K. Eguchi, *Appl. Catal., B*, 2005, **57**, 211–222.
- 47 S. Zhu, X. Gao, Y. Zhu, W. Fan, J. Wang and Y. Li, *Catal. Sci. Technol.*, 2015, **5**, 1169–1180.
- 48 C. Yang, Z. Miao, F. Zhang, L. Li, Y. Liu, A. Wang and T. Zhang, *Green Chem.*, 2018, **20**, 2142–2150.
- 49 L. Vivier and D. Duprez, *ChemSusChem*, 2010, **3**, 654–678.
- 50 D. Mullins, S. Overbury and D. Huntley, *Surf. Sci.*, 1998, **409**, 307–319.
- 51 A. Chen, X. Yu, Y. Zhou, S. Miao, Y. Li, S. Kuld, J. Sehested, J. Liu, T. Aoki and S. Hong, *Nat. Catal.*, 2019, **2**, 334.
- 52 H. Chen, Q. Wang, X. Zhang and L. Wang, *Appl. Catal., B*, 2015, **166–167**, 327–334.
- 53 H. Chen, Q. Wang, X. Zhang and L. Wang, *Ind. Eng. Chem. Res.*, 2014, **53**, 19916–19924.
- 54 M. García-Melchor and N. López, *J. Phys. Chem. C*, 2014, **118**, 10921–10926.
- 55 E. Kukulska-Zajac, P. Kozyra and J. Datka, *Appl. Catal., A*, 2006, **307**, 46–50.
- 56 A. Dubey, L. Nencini, R. R. Fayzullin, C. Nervi and J. R. Khusnutdinova, *ACS Catal.*, 2017, **7**, 3864–3868.
- 57 X. Shao, X. Yang, J. Xu, S. Liu, S. Miao, X. Liu, X. Su, H. Duan, Y. Huang and T. Zhang, *Chem*, 2019, **5**, 693–705.

